SANDSTONE DIAGENESIS: ESTABLISHING THRESHOLD TEMPERATURE AND DEPTH OF POROSITY DETERIORATION, PENYU BASIN AND TENGGOL ARCH, OFFSHORE PENINSULAR MALAYSIA

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ABSTRACT

A review of clastic sandstone reservoirs from the Penyu Basin and Tenggol Arch area has revealed that the deepest, stratigraphically oldest and potentially overpressured reservoirs are affected by diagenetic alteration of reservoir mineral components. There is a marked discrepancy between measured reservoir temperature and calculated reservoir temperature based on vitrinite reflectance data in several investigated wells. Assuming a relatively constant temperature gradient in the basin during the Pliocene to recent time, quartz cementation started at a paleo-depth of ca. 2000m tvdss or 105°C, and porosity was mostly destroyed at a depth of ca. 3000m tvdss and 130°C. This said, there is a strong stratigraphic correlation between pre-Oligocene sediments with high vitrinite reflectivity readings, and a strongly elevated contemporaneous temperature gradient. Therefore, the scope for deep oil and gas drilling maybe reduced in at least some parts of the basin, where oil is found locked in diagenetically altered pore spaces. In addition, geological data also suggest that the Penyu Basin is very complex and may have stronger affiliation with pull-apart rather than with rift basins.

***Key words**: diagenesis, inclusions, Penyu Basin, quartz cementation, Tenggol Arch, vitrinite reflectance*

INTRODUCTION

The Penyu Basin lies south-west of the Malay Basin and straddles the Malaysia-Indonesia maritime boundary (Figure 1). The stratigraphic summaries of the Penyu and Malay basins are illustrated in Figure 2, and the former is subdivided into lithostratigraphic units such as the Penyu, Pari and the Pilong formations; with age ranging from the Early Oligocene to the Pleistocene, and sometimes described in terms of syn-rift to post-rift sequences separated by erosional unconformities. A seismic type section for the basin is illustrated in Figure 3.

In a rich and productive basin, hydrocarbon charge and migration may be inferred from the spatial distribution of discovered accumulations and by assuming the presence of a kitchen down dip of the accumulations. However, rarely is the hydrocarbon migration phenomenon observed or physically demonstrated by well data without further detailed fluid inclusion investigation. In general, the generative source rocks are seldom penetrated by the wells, which are commonly drilled on structural highs. Therefore, in a less explored basin or frontier basin, more effort is often invested to demonstrate the presence of hydrocarbons, as proof of a key component of a working petroleum system.

Quality of reservoir is (perceived as perhaps) one of the most important risk factors in any exploration and appraisal campaign. Oil companies spend significant money in studying reservoir environments, and related statistics for porosity and permeability distributions of various depositional settings. Unfortunately, reservoir diagenesis data are often either forgotten, neglected or the available data are not thoroughly studied by licensed operators. In a previous paper by Maga et al. (2015), the authors highlighted fluid inclusions in quartz as indicators of oil migration timing and reservoir diagenesis, and that oil migration came along with mineral brines. Here, we focus on analysis of reservoir temperatures as determined by logs (present-day basin temperature regime) and vitrinite reflectance data (historical basin temperature regime). Both have important implications for assessing the optimum depth of exploration targets in the Penyu Basin and Tenggol Arch area.

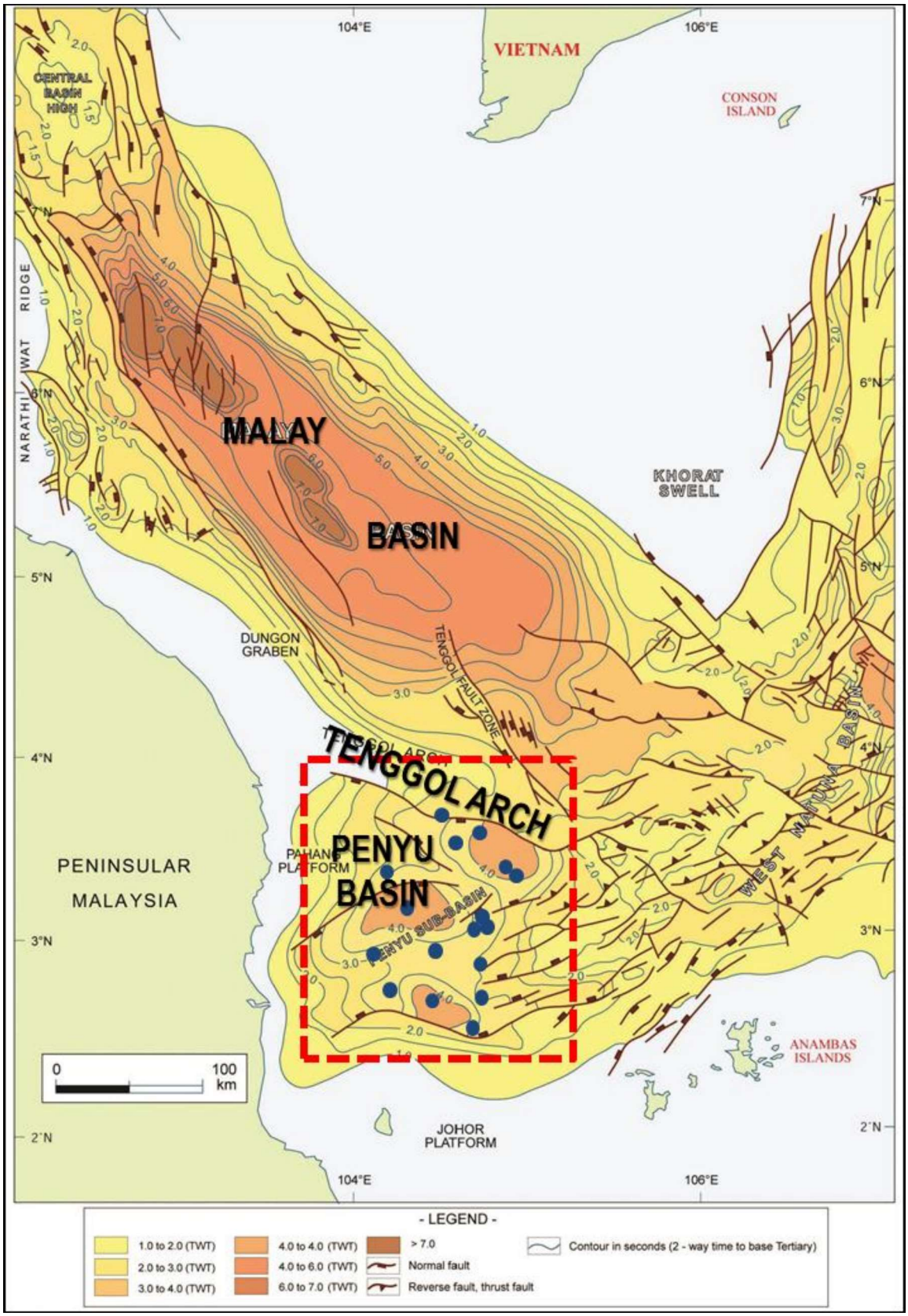


Figure 1: *Structural framework map of the Malay and Penyu basins, offshore Peninsular Malaysia. The study area covering the Penyu Basin and Tenggol Arch area is outlined in dashed red line (after IHS Energy, 2010). Blue dots annotate locations of well investigated by Maga et al. (2015), where quartzes with fluid inclusions are reported.*

EXPLORATION HISTORY AND PETROLEUM SYSTEM

The Penyu basin-filling sediments are of terrestrial and fluvio-lacustrine origin, and punctuated by marine sediments from the occasional periods of ingression (Figures 2 and 3). A number of source rock intervals have been identified (from Late Oligocene to Early Miocene sequences of equivalent Groups K and L in the Malay Basin, and questionable Eocene), and there are at least two pulses of oil migration observed (e.g., Tan, 2009). The main reservoirs in the Penyu Basin are siliciclastic, deposited mainly in fluvial-lacustrine channels and deltas, with varying grain sizes from (rarely) coarse, middle to fine sands.

As summarised by Maga et al. (2015), the basin has been explored since 1968 (pre-PSC days) when Conoco was given a concession that once covered the entire basin. To-date, there have been more than 20 exploration wells drilled, mainly on Miocene (post-rift) inversion structures. So far exploration efforts have resulted in one oil discovery at Rhu-1 in 1991 in late "syn-rift" sediments in basement-drape structure (Madon and Azlina Anuar, 1999), and uneconomic discoveries/reasonable shows and in a few other wells (e.g., A-1, J-1; Figures 3 and 4). Recent exploration drilling in the Cherating Half Graben had confirmed the presence of abundant live oil in the mid "syn-rift" section despite the apparent dearth of good reservoir rocks (C-1, J-1; Figure 4). The Rhu-1 well encountered oil in fluvial Oligocene "syn-rift" sandstones. The Rhu oil is light (API 35°), moderately waxy and of high pour point (44 °C). With Oligocene-Miocene levels only marginally mature for oil, charge is inferred to stem from Eocene-Oligocene age isolated pods of lacustrine source with potential contribution from coal and coaly shale layers.

The Rhu discovery is evidence of a functioning petroleum basin (Tan, 2009), where in the case of Rhu-1, a clear case of vertical oil migration can be made. Some oils trapped in reservoirs and fluid inclusions are low-gravity, suggesting oil migrated through the conduits at low temperatures, implying limited rock overburden, and likely early migration during the Early Miocene. The Rhu-type light oils probably originated during a secondary, later migration pulse, and the relatively high reservoir temperatures have prevented biodegradation.

Hydrocarbon-bearing reservoirs in the Penyu Basin are (with the exception of Rhu) of mostly poor quality and are located in the Oligocene and pre-Oligocene sections. A recent sequence stratigraphic study by Barber (2013) suggests that the depositional system of the Penyu Basin is mainly composed of restricted fluvio-lacustrine facies up to Base Miocene level, and was isolated from the fluviatile sedimentary pulses of the Malay Basin to the north by the intervening saddle of the Tenggol Arch until Early Miocene time (Figure 3). Post-Early Miocene, the Penyu and the Malay basins practically formed a united sedimentary system of mainly fluvio-terrestrial and shallow marine deposits sourced from the north culminating in a major inversion episode in the study area.

GEOLOGICAL SETTING

The Penyu Basin and the more well-known Malay Basin are part of a system of the Cenozoic sedimentary basins developed along a major zone that stretches from the Gulf of Thailand to the Natuna region. Different geological and tectonic models have been proposed to explain the origin of the basins, as discussed recently by Tan (2009). The basins are considered to have originated either in a back-arc setting (Kingston et al., 1983; Mohd Tahir et al., 1994), or as a pull-apart basin developed along a major strike-slip fault (Tapponier et al., 1982), or through thinning of continental crust (White and Wing, 1978). Other tectonic models involve crustal extension over a hot spot (Hutchison, 1989; Khalid Ngah et al., 1996), extensional subsidence along a major left-lateral shear zone (Madon and Watts, 1998; Md Yazid et al., 2014) and as a failed rift arm of a triple junction above a mantle hot spot (Tjia, 1999). Morley and Westaway (2006) proposed a geodynamic model of the Malay Basin, involving lower-crustal flow in response to post-rift sedimentation.

Most of these models are regional in nature and were crafted without the benefit of offshore data. However, in recent years we have seen widespread acquisition of Tensor gravity and 3D seismic data, as well as marine gravity data. The data show a thoroughly sheared crust with basement (granite, metamorphic rocks, and basalts) forming elongated slivers along a number of strike-slip faults, particularly at the edges of the Tenggol Arch (Ng, 1987; Figures 1 and 5). Accordingly, we believe that the basins were originated as pull-apart basins on top of a highly sheared continental crust, which started to subside at the end of the Eocene. According to this model, there may not have been any extension in the sense of pure rifting as such, but instead pulses of basement shear that resulted in elongated sag basins (Maga et al., 2015).

The Penyu Basin is tectonically complex and has seen at least two phases of major strike-slip tectonism and inversion; the older and very widespread inversion occurred intra-Oligocene, with a weaker and localized one in the Miocene. This may have had the effect that originally channelized reservoir bodies were compartmentalized even further.

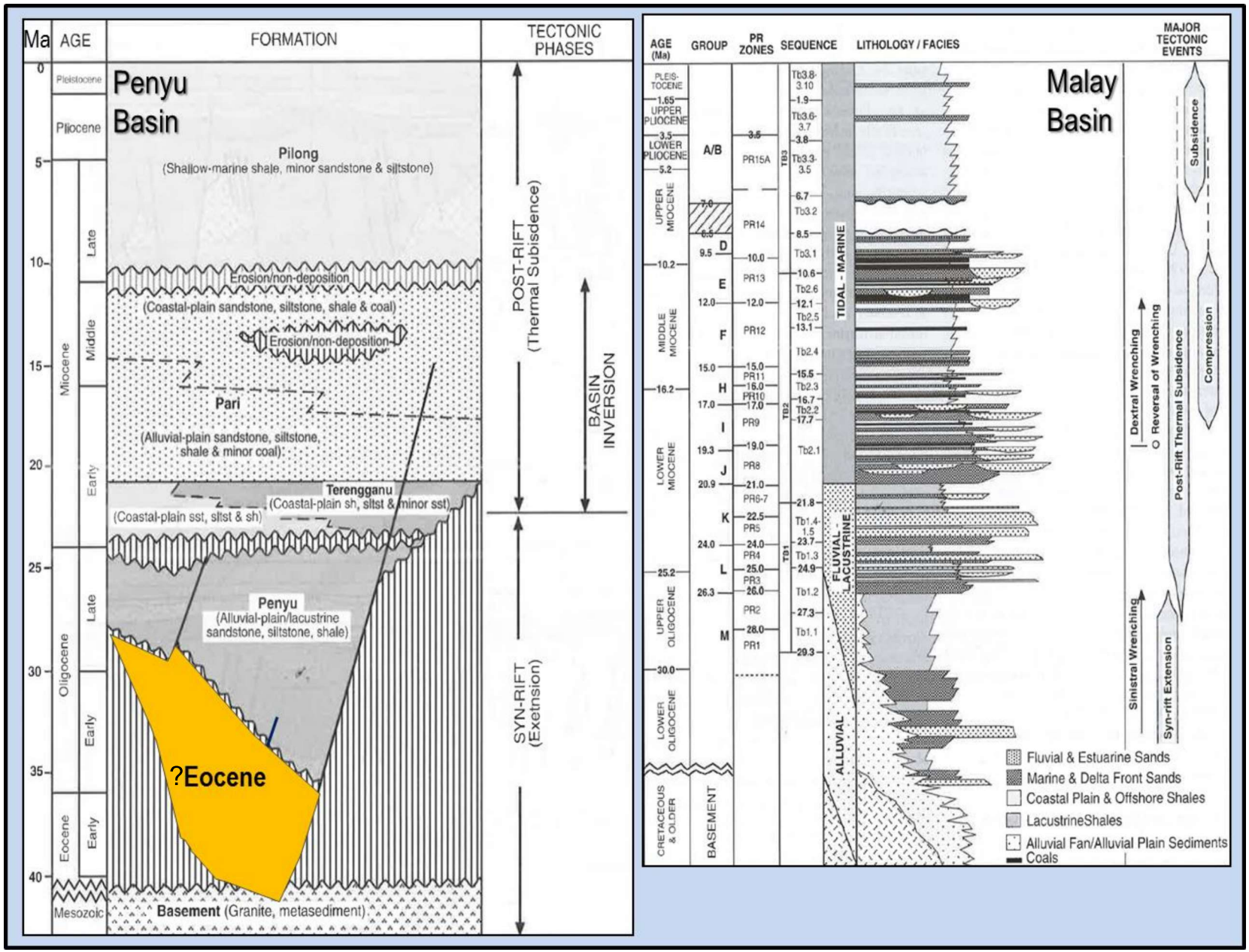


Figure 2: *Comparison of Penyu and Malay basins stratigraphy modified after Tan (2009), originated from Madon and Azlina Anuar (1999, Penyu Basin) and Madon et al. (1999, Malay Basin).*

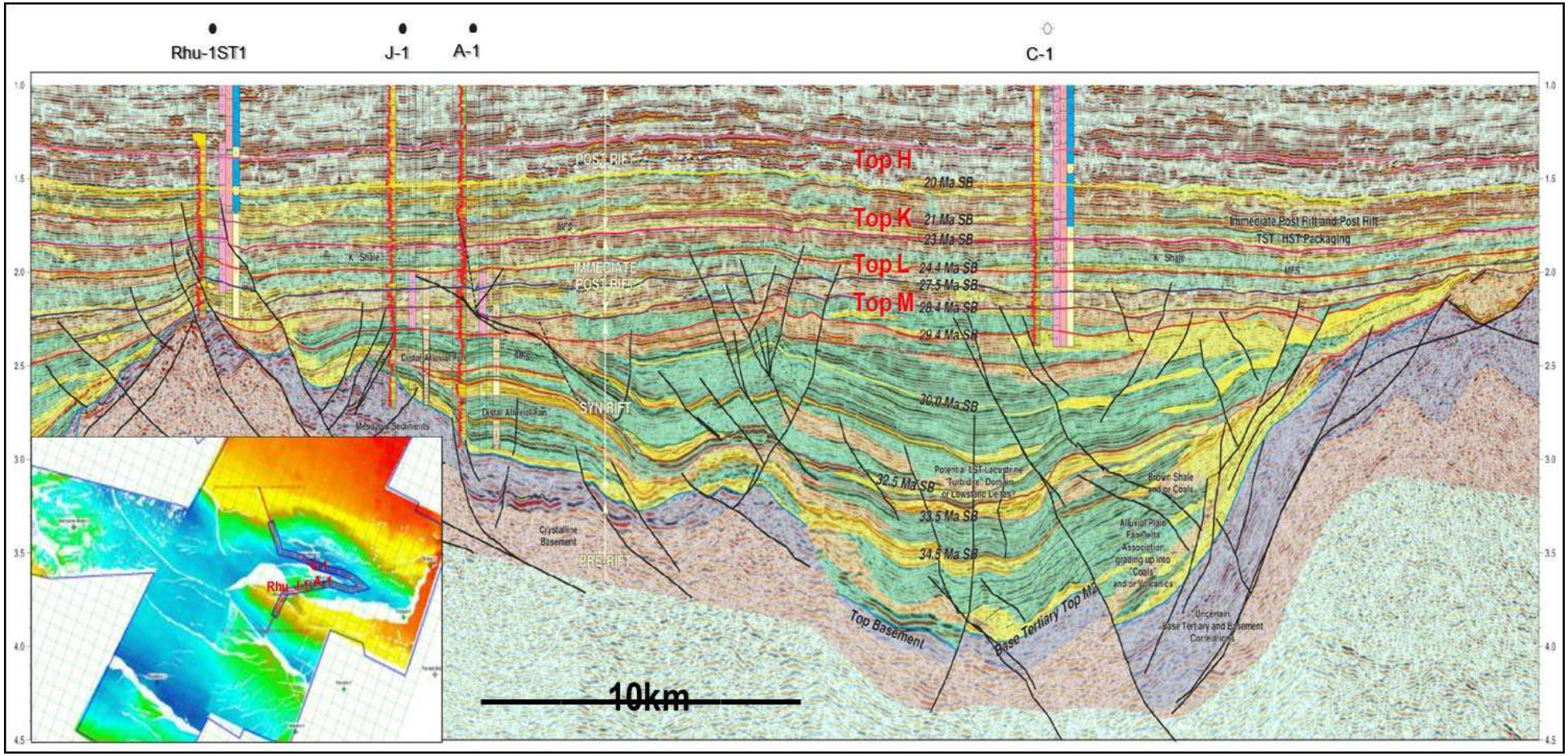


Figure 3: *Penyu Basin regional seismic section illustrating mapped sequence boundaries (SB) and related depositional facies; yellow = sandy facies, green = lacustrine shales, purple = meta-sediments. The depositional system of the Penyu Basin comprises mainly restricted lacustrine facies up to Base Miocene, near Top L event and was isolated from the fluvial sedimentary pulses of the Malay Basin until this time, from Maga et al. (2015) and after Barber (2013).*

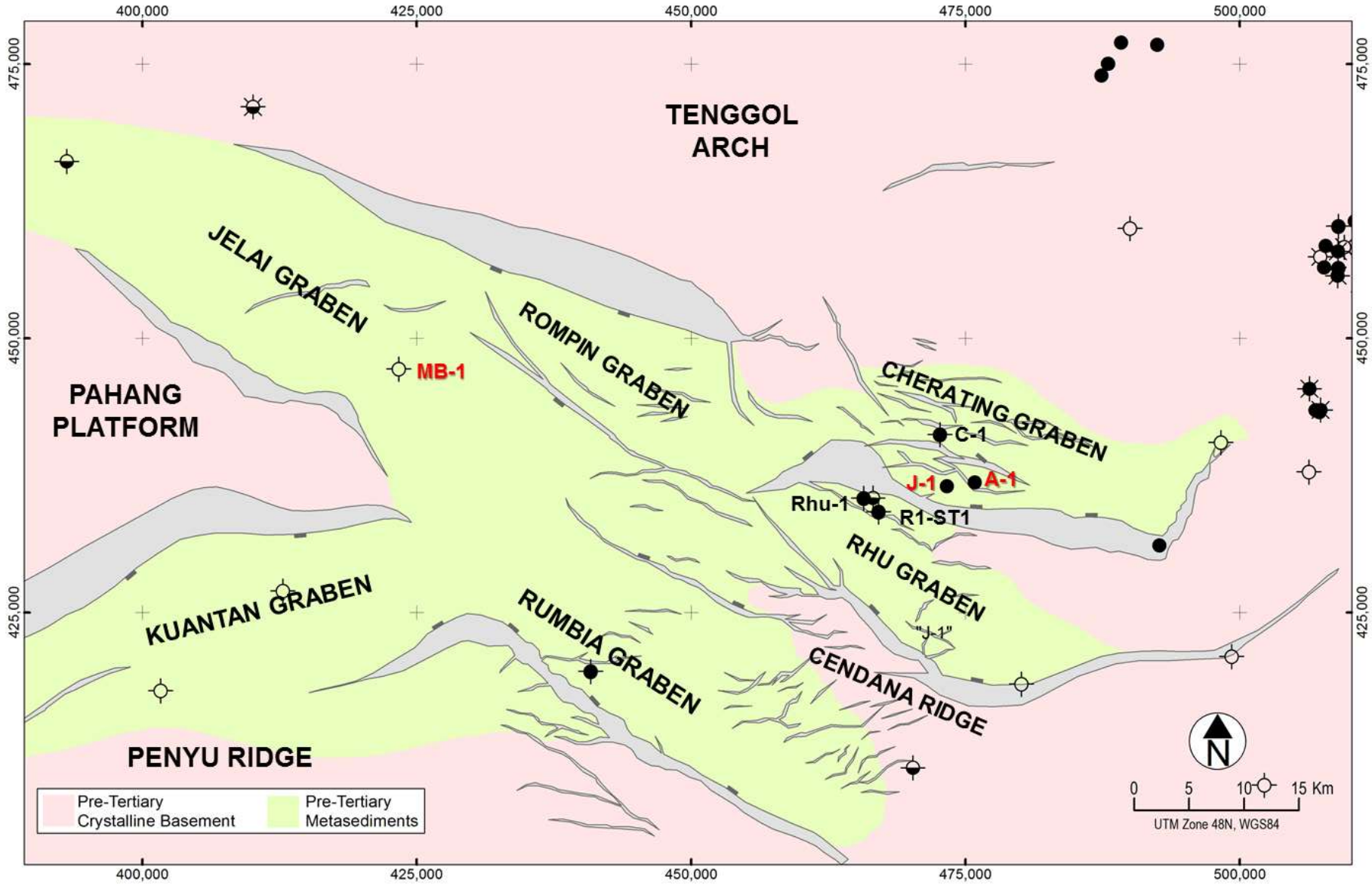


Figure 4: *Exploration wells and structural elements of the Penyu Basin (well status from IHS Energy). Wells MB-1, J-1 and A-1 as highlighted in red were investigated for porosity and temperature versus depth relationships (modified after Maga et. al., 2015).*

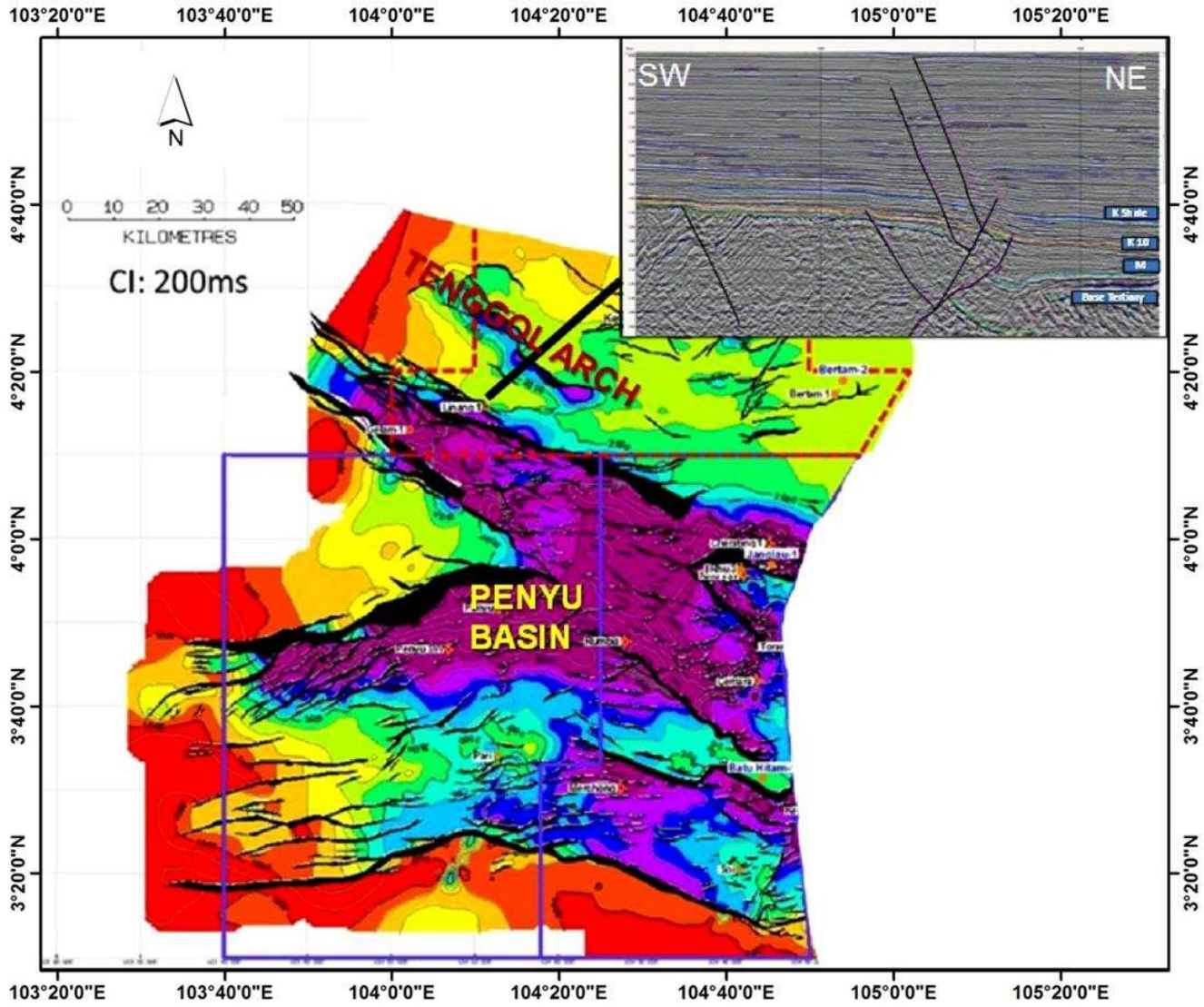


Figure 5: *Base Tertiary (Top Basement) map over the Penyu Basin and Tenggol Arch showing strike-slip faulting at the southern edge of the latter. Purple zones represent half-grabens and depocentres and indicate the land-locked nature of the basin at the time. Inset is a SW-NE seismic section that illustrates the basement faulting over the Tenggol fault zone (from Maga et al., 2015).*

INVESTIGATION METHODOLOGY – RESERVOIR PETROGRAPHY AND SANDSTONE DIAGENESIS

Fluid inclusions in authigenic cements can be measured directly from thin sections. Unfortunately, to the best of our knowledge none of the oil companies that operated in the study area carried out micro-thermometry on any sample. Alternatively, an indirect method is used whereby the depth of occurrence of both quartz cements and fluid inclusions is recorded and compared with borehole temperature and vitrinite reflectance data. Vitrinite reflectance is correlated with temperature using the formula by Barker and Pawlewicz (1995). If there is no significant difference between the measured borehole temperature (which is derived from various sources, in the order of descending quality: DST, MDT, wireline log headers) and vitrinite-derived maximum temperature, it can be assumed that the heat flow history of the area had been stable over time, and that the present-day borehole temperatures represent the fluid temperatures at the time of cementation.

There are only few studies conducted on the depositional histories of sediments in the Penyu Basin, with little published information available on its diagenetic history whereas most studies were focused on the Malay Basin instead (e.g., Nik Ramli, 1986, 1988; Ibrahim and Madon, 1990; Chu, 1992; Madon, 1994). Chu (1992) carried out a comprehensive basin-wide petrographic study of sandstones in the Malay Basin, using 241 samples and established the main porosity reduction mechanism to be mechanical compaction down to a depth of about 1200m tvdss (see also Madon, 1994). Beyond this depth, chemical processes took over, including cementation by quartz or, more rarely, calcite, siderite, pyrite and clay minerals (Figure 6).

Uplift and erosion in some parts of the Malay Basin (especially in the south) resulted in secondary porosity by dissolution of framework grains, including feldspar. These are recognised from the presence of oversized pores left by dissolution of framework grains (Nik Ramli, 1986; Ibrahim and Madon, 1990). Hence, more secondary porosity is expected to occur in sandstones with moderate percentage of lithic/feldspathic grains compared to "clean" quartzose sandstones. This is ultimately tied to the provenance and depositional environments of the sandstones (Ibrahim and Madon, 1990).

Madon (1994) studied the sandstones in Jerneh Field in northern Malay Basin, and observed increase in quartz overgrowths with depth, from an average of 1% at 1270m tvdss to 7% at 1940m tvdss. Quartz overgrowths begin at about 90 – 100 °C. The amount of quartz cementation appears to be increasing with age and depth of burial too (Chu, 1992), and also appear more prevalent in "clean" sandstones (Madon, 1994).

DATABASE

The study area covers the main Penyu Basin and the Tenggol Arch area (Figure 1), previously operated by PETRONAS Carigali, Conoco, Texaco and more recently Lundin Petroleum and JX Nippon partnership. The database for this study consists of 12 exploration wells previously investigated by Maga et al. (2015; Figure 7), where wireline logs, cuttings evaluation, fluid inclusion stratigraphy (FIS), and thin-section petrographic analyses are available. The latter two studies were provided mostly by Fluid Inclusion Technologies, Inc. (Tulsa) and Corelab (Kuala Lumpur), respectively.

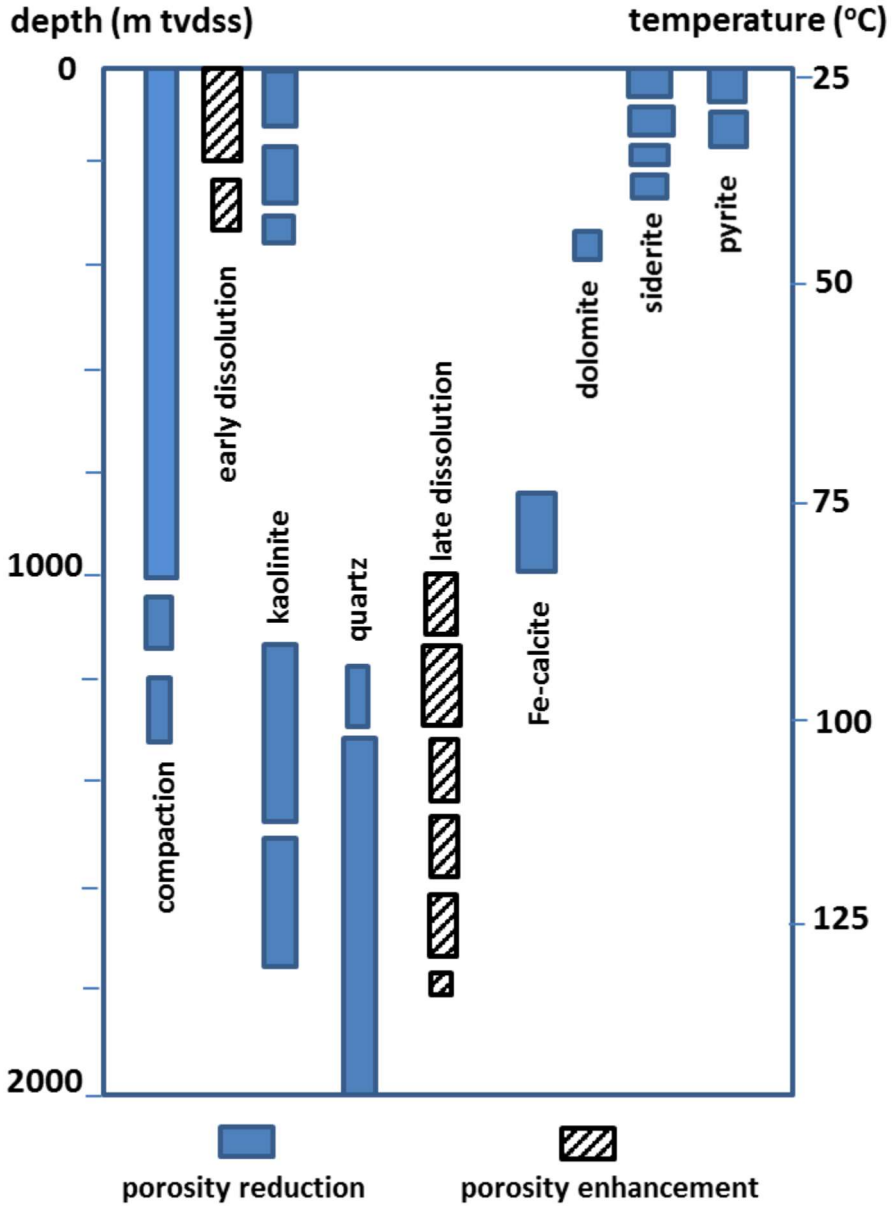


Figure 6: *Diagenetic sequence in the Malay Basin, based on Madon (1994).*

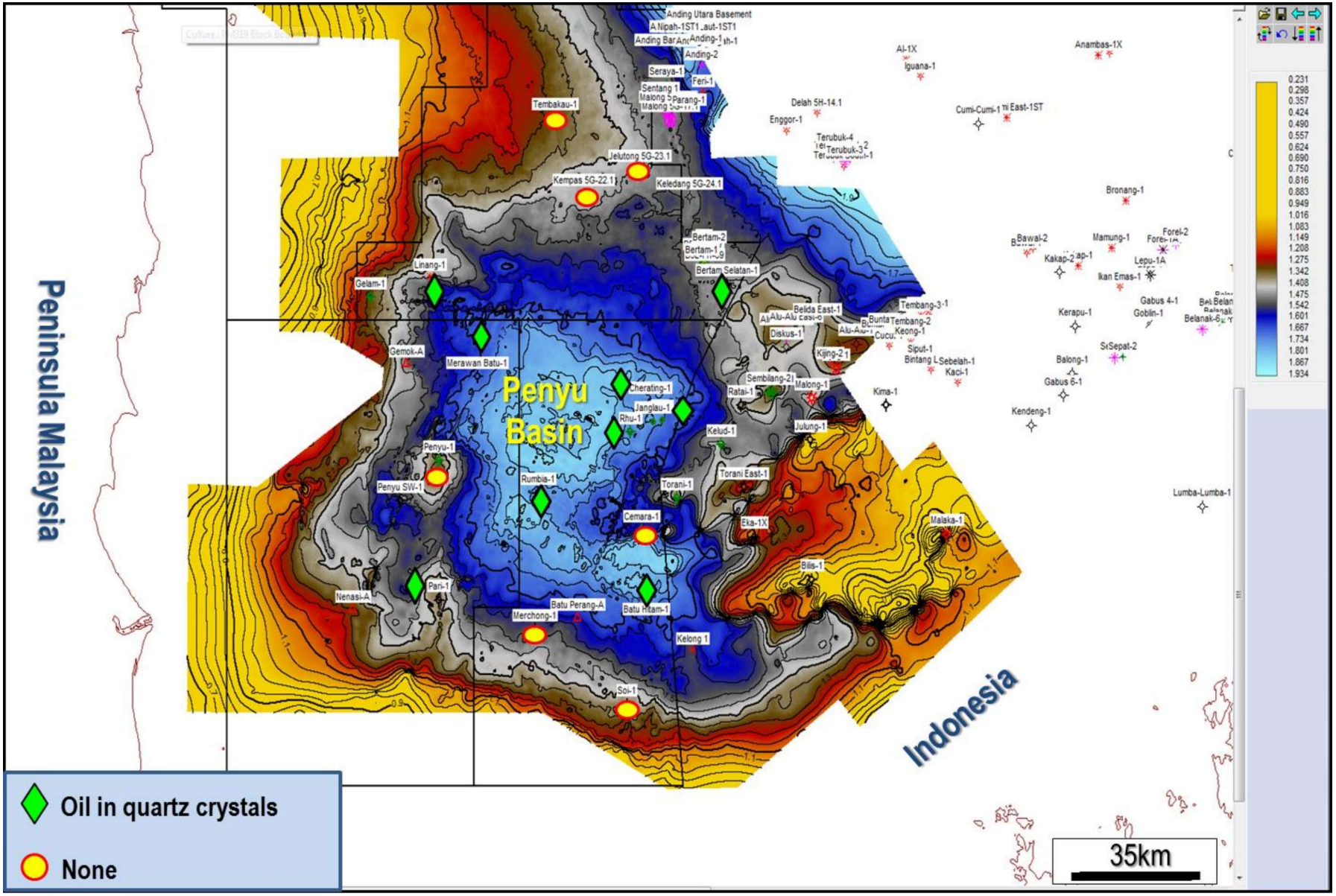


Figure 7: *Locations of investigated wells and occurrence of oil inclusions as summarised by Maga et al. (2015). Blue areas denote Penyu depocentre, with depth contour map (in second TWT) of the Oligocene "K" shale level shown (modified after Maga et al., 2015).*

POROSITY, QUARTZ CEMENTATION AND WELL TEMPERATURE RELATIONSHIP

Lander and Walderhaug (1999) had established kinetic models of quartz cementation in which quartz cementation starts at an effective threshold temperature of around 70 – 80 °C. Oelkers et al. (2000) suggested that cementation is a continuous process, with cement developing as a function of both temperature and quartz surface area, and with most cement precipitating between 100 - 120°C. Harwood et al. (2013) performed isotope analyses on sandstone from the Jurassic Ness Formation from the North Sea to reveal the growth history of single quartz overgrowths to a resolution of 2 µm. Measured $\delta^{18}O$ (cement) range from +28 to +20‰ V-SMOW in early to late cement and are consistent with quartz cementation models that propose the bulk of quartz precipitates as a continuous process beginning at 60 – 70°C.

A comparison of three Penyu wells (MB-1, A-1 and J-1), shows different porosity decline patterns (Figure 8). Most likely, the observed porosity decline is strongly shaped by quartz cementation. In the Penyu Basin, there are two important diagenesis boundaries:

(i) Beyond the porosity-reducing mechanism of mechanical compaction, the onset of destructive diagenesis starts with mineral cementation, in particular quartz cement. This boundary is found in the Malay Basin at around 1200m tvdss (Chu, 1992; Madon, 1994) and in the Penyu Basin between 1800 and 2000m ahbdf (along hole below derrick floor with DFE of 20m, Figure 9). Depending on the temperature gradients in these basins, these depths correspond to temperatures ranging from 105 – 130°C in Penyu Basin (Figure 9), and 90 - 100 °C in the Malay Basin (Madon, 1994). Below this depth, diagenetic processes appear to have affected permeability more than porosity, as the pore throats and smaller pores are occluded by quartz and clay cements. In larger pores, fluids (occasionally oil) may be preserved but these are no longer mobile. A similar pattern of diagenesis is observed in most of the studied wells (Figure 10).

(ii) The depth at which permeability destruction is deemed complete is at around 2800-3000m tvdss. At this depth, authigenic cements have occluded the pore spaces and only some isolated porosity remains. In clean sandstones, most of the permeability is destroyed by quartz cementation, and clay minerals such as kaolinite, especially in clay- or feldspar-rich intervals (Figure 11). However, as observed in Figure 8, where an increase in porosity values is noticed in J-1 and A-1 wells located in the Cherating Half-Graben at depth around 3250m ahbdf, it is thought that a deep overpressured formation might have preserved porosity, albeit with the associated reduction in permeability by chemical compaction, which would have likely continued, independently of overpressure, of these deep reservoirs (e.g., Mohammad Jamaal, 2003).

The stratigraphy of the Penyu Basin (Figure 2) is characterized by a varying thickness of pre-Oligocene strata, and a mighty Oligocene section covered by a blanket of Neogene in the order of some 1200m thickness. There was mild tectonism during the Miocene, with a locally prominent, Serravallian tectonic inversion along a number of fault lines (Maga et al., 2015). In the Rhu area, the well data indicate a temperature gradient of between 3.3 and 4.0°C/100m (Figure 9). The temperature gradient is fairly uniform throughout the borehole but increases in the bottom hole (Oligocene) section of the wells; most likely as a result of higher formation density and thermal conductivity. This uniformity is broken by, a very important jump in vitrinite readings from 0.7 to 1.0 VRM in the bottom hole section of wells A-1 and J-1 with calculated sediment removal of more than 1000m, indicating an important unconformity (Figure 12). Sandstone samples (cuttings) of the J-1 bottom-hole sequences show strongly welded quartz and feldspar grains (Figure 13). The heat gradient in the bottom hole section (6°C/100 m) is also strongly elevated in respect to the shallower (Oligo-Neogene) sequence with 3°C/100m only. Figure 14 shows a gridded depth map, a compilation of the temperature gradients calculated from the borehole temperature measurements in the Penyu Basin and Tenggol Arch area. The gradients range from 2.7 to 6°C/100m. Recently drilled deep wells (> 4000m, J-1 and A-1) in the Cherating Half-Graben, however, recorded these anomalously high bottom hole section gradients of 5-60C/100m. The cause of these high gradients is yet unknown but maybe the consequence of the wells being located in a “hotspot” area.

In respect to oil migration and reservoir diagenesis, it is possible or even likely, that pulses of hot water brines flushed carrier beds together with oil or alternated with the latter. Sections of the bottom hole sequence in wells J-1 and A-1 presented strong oil shows with reasonable porosity preservation (Figure 11). However, there was evidence of low permeability: oil appeared to be locked in diagenetically secluded pore space and could not escape from the reservoir fabric. This may also explain the overpressures observed in hydrocarbon-bearing intervals. The process is shown schematically in Figure 15.

Based on the temperature/geothermal gradient data, and our understanding of quartz cementation and its relationship with temperature gradient, a spatial distribution of porosity destruction by quartz cements is shown in Figure 16. Ultimately, these

temperature gradients and porosity threshold maps are indicative of the exploration risk that oil companies are facing when exploring deep reservoir targets.

Discovery of oil-bearing but tight reservoir rock is regarded as technical success, but economic success depends to a large extent on reservoir permeability, as well as reservoir continuity.

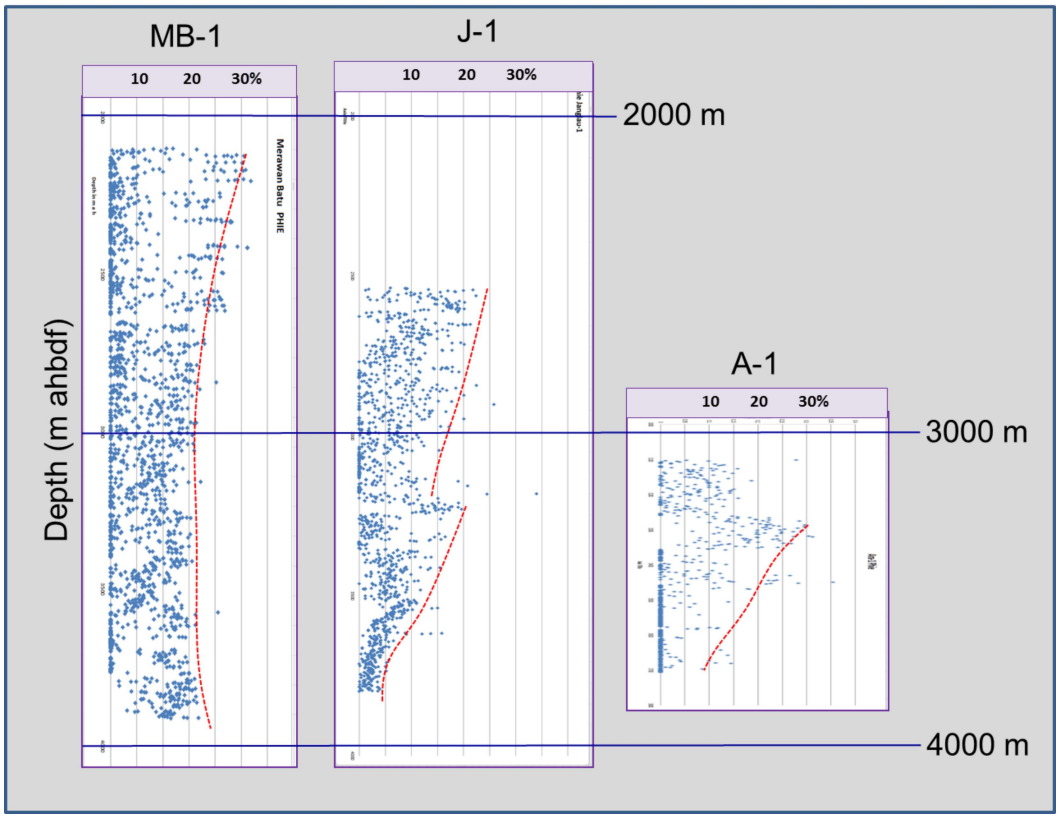


Figure 8: *Porosity comparison at depth (in meters along hole below derrick floor) between three Penyu Basin exploration wells; MB-1, J-1 and A-1. See Figure 5 for well locations.*

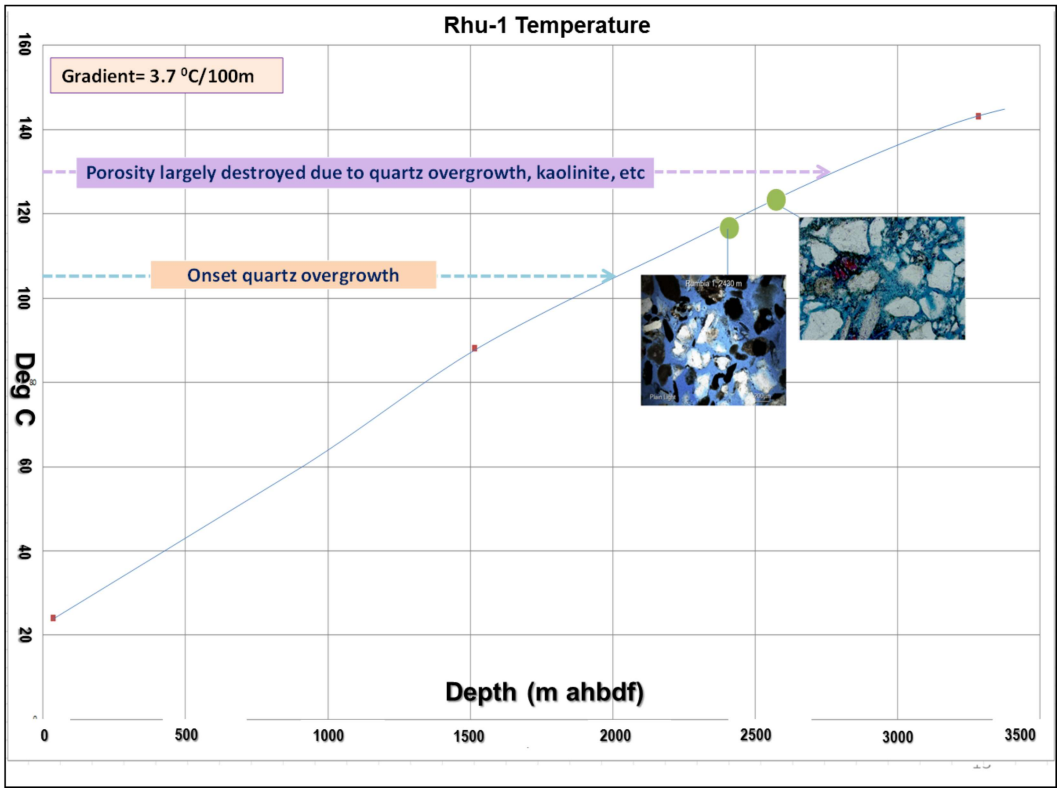


Figure 9: *In the study area, quartz overgrowth starts at a depth > 1800 - 2000 m ahbdf, depending on the respective temperature gradient rather than on stratigraphic unit (from Maga et al. 2015).*

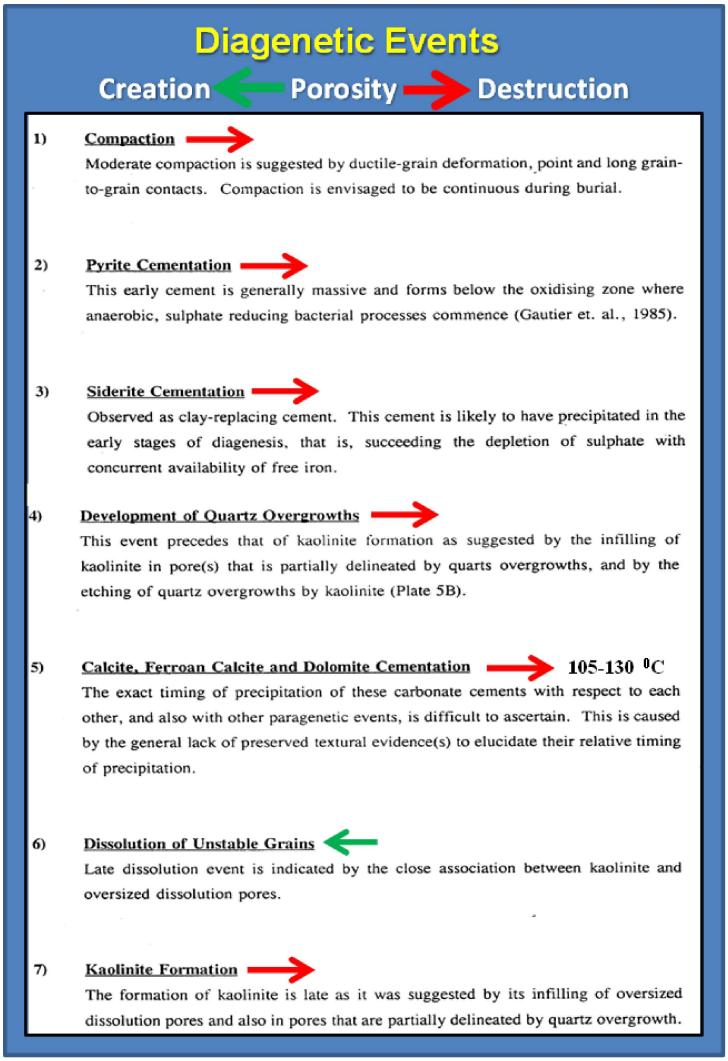


Figure 10: *Common patterns of diagenesis affecting reservoir rock at increasing depth, temperature, and pressure. Mobilized quartz builds up layers of cement, with the outcome that permeability in sandstone reservoirs is destroyed gradually (from Maga et al., 2015).*

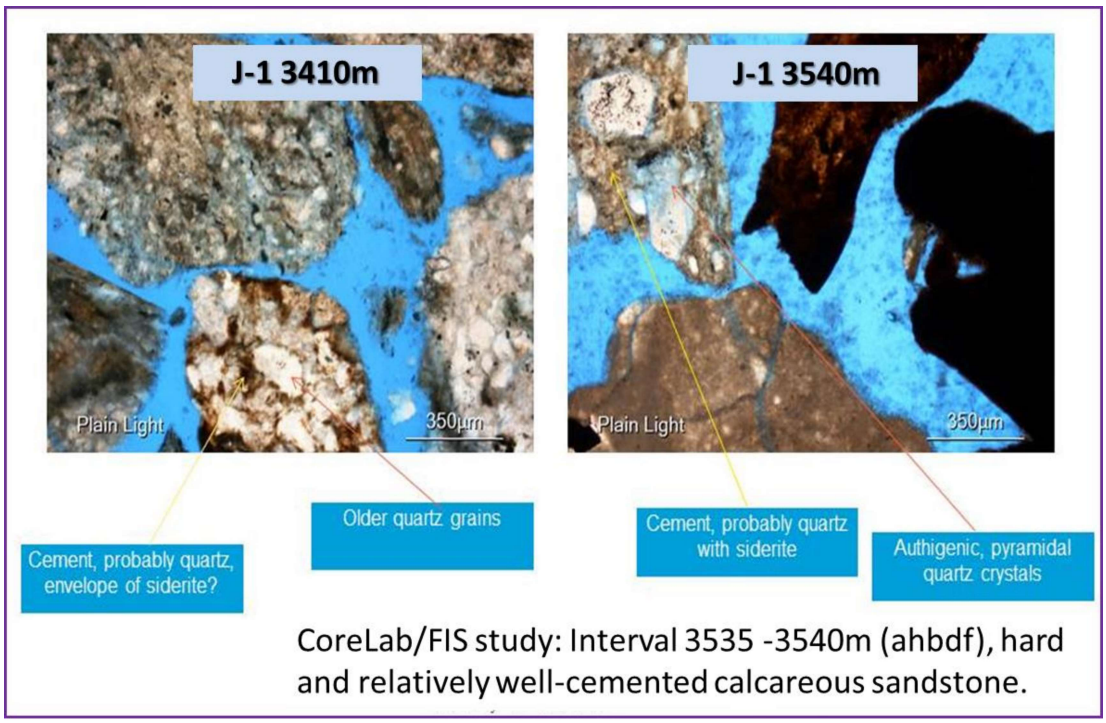


Figure 11: *Miscellaneous cuttings from well J-1, show a strong recrystallization, leading to the occasional growth of authigenic quartz crystals. There is little or no reservoir potential present in these samples (from Maga et al., 2015).*

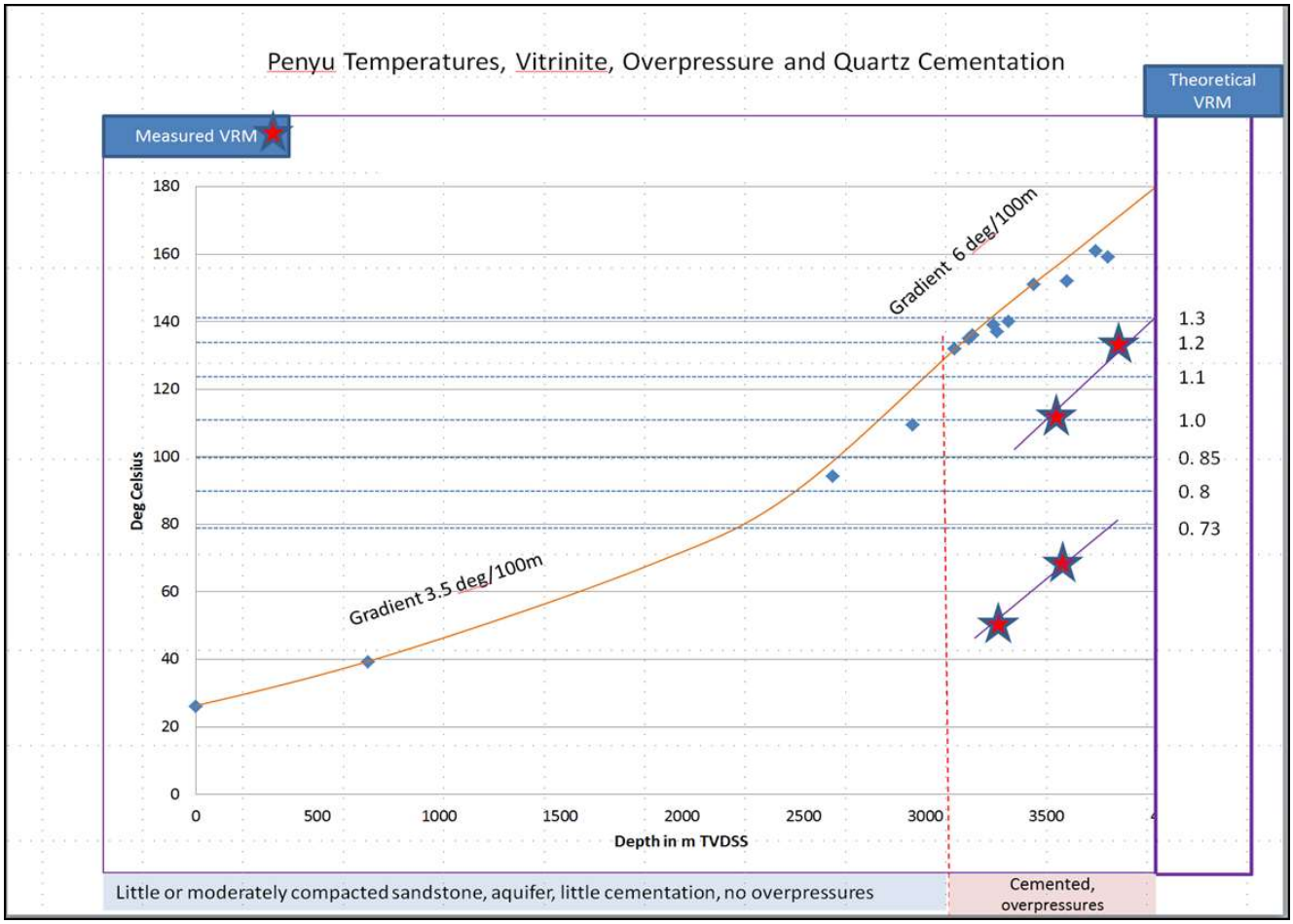


Figure 12: *Well J-1 temperature, VRM and depth relationship. Borehole temperatures and vitrinite reflectivity data, converted to °C using the Barker and Pawlewicz formula (1995) are well aligned on the bottom hole section of the well (> 2500m tvdss) with a much higher temperature gradient than the upper hole section, which belongs arguably to a much older (? Mesozoic) stratum. This observation points to a significant stratigraphic gap of some 1000 - 2000 m missing sediment.*

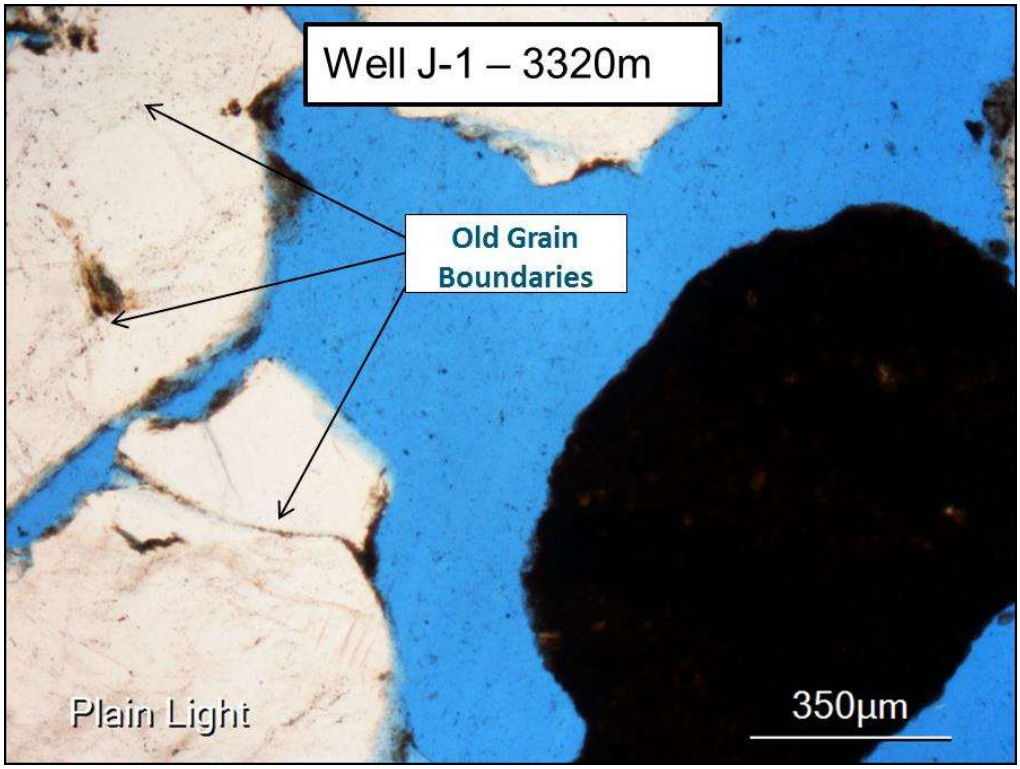


Figure 13: *Grain-to-grain contact in Well J-1 at 3320m (ahbdf). The cuttings show strongly welded quartz and feldspar grains, with hardly any cement being visible.*

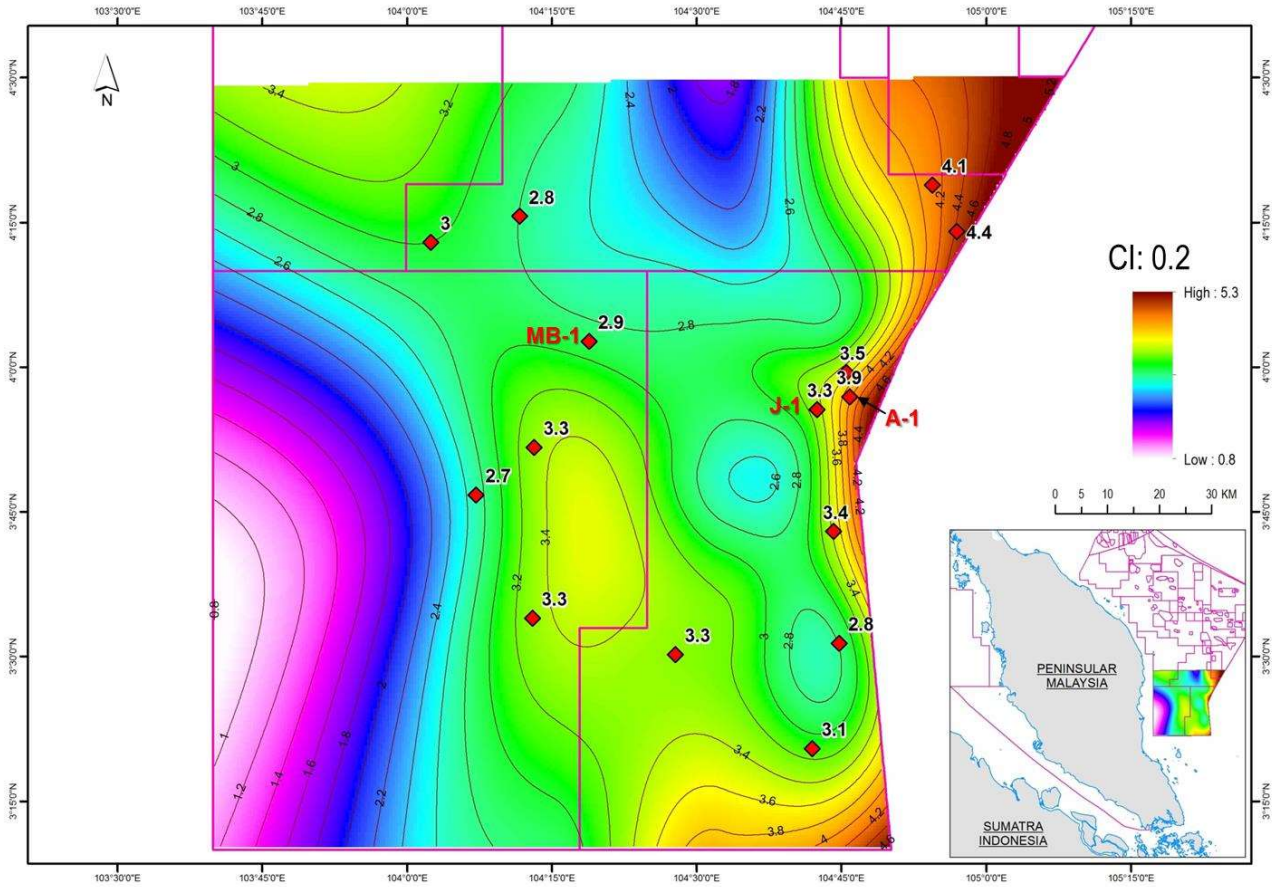


Figure 14: *Penyu Basin and Tenggol Arch - temperature gradients (°C/100m) calculated from borehole measurements, DST and wireline temperatures (from Maga et al., 2015).*

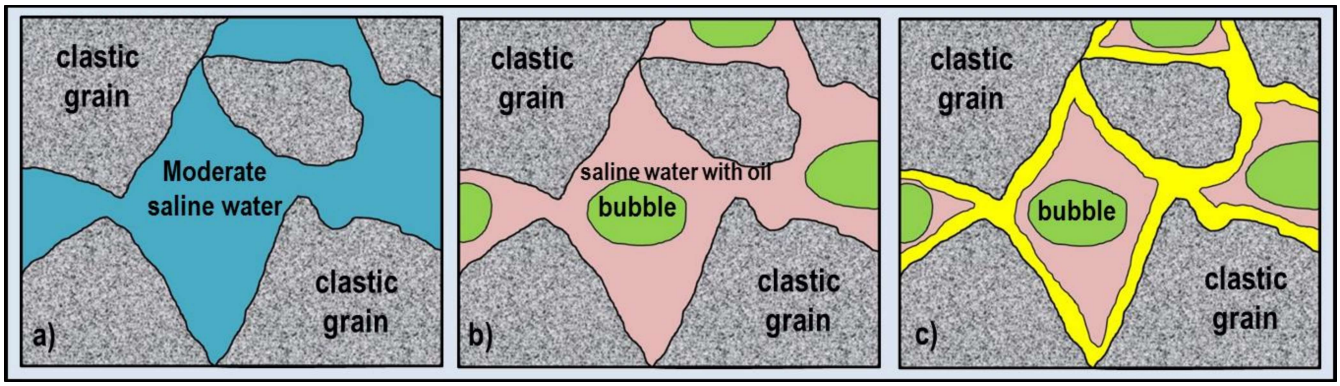


Figure 15: *A schematic summary of oil migration and reservoir diagenesis. a) Pre-diagenetic stage < 80 °C - moderately saline water fills pore spaces between clastic grains. b) Oil migration and salty brine ca. 100 °C - saline water with oil enters pore spaces. Mixing of salty brine with porefill water, and oil forms bubbles (green) in the centre of pore spaces. c) Destructive diagenesis ca. 120 °C - quartz and kaolinite (yellow) grow along the margins of the clastic grains (= syntaxial overgrowth). Oil is trapped, there is no permeability left, and porosity is strongly reduced. Oil bubbles were pressurised and shrank.*

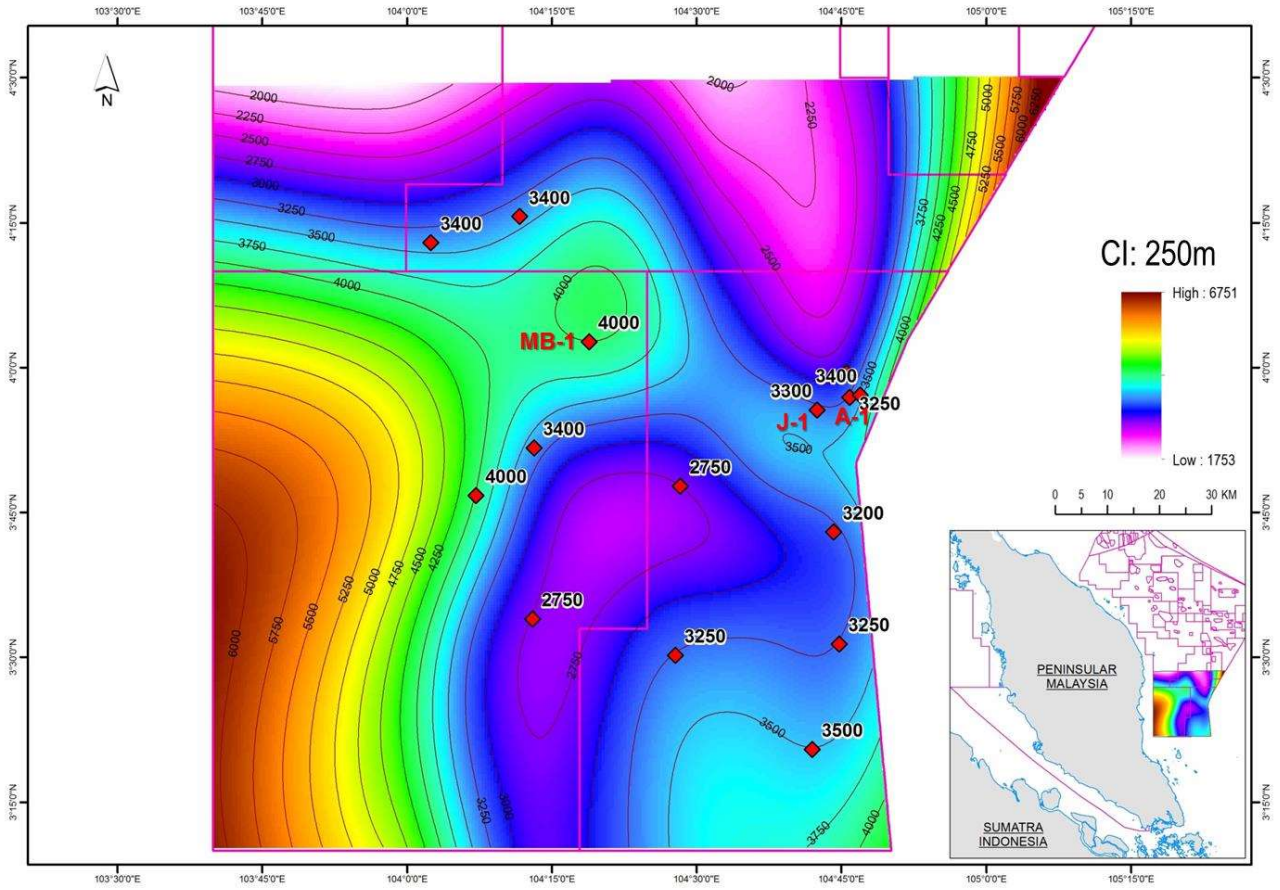


Figure 16: *Penyu Basin and Tenggol Arch - porosity is largely annihilated by quartz cement/overgrowth, below indicated depth levels (m tvdss), @ 130 °C (modified after Maga et al 2015).*

DISCUSSION

Temperature and vitrinite reflectivity comparisons indicate, that the Penyu Basin may be far more complex than previously thought. In particular, we notice the effect of repeated strike-slip movements, having affected the basin possibly during pre-Oligocene, and confirmed during Oligocene and, somewhat less so, in Neogene time. Therefore, the Penyu Basin may constitute a pull-apart basin, rather than a rift basin. Furthermore, a comparison between the wells: MB-1, J-1 and A-1 and Rhu-1 points to the presence of an older remnant, a pre-Oligocene sediment sequence, located in the centre of the basin, and displaying high vitrinite reflectivity values. This sequence is poorly dated but may contain Eocene and perhaps even Cretaceous strata. Most likely, this part of the basin has seen removal of pre-Oligocene sediments of more than 1000m. This may point to pre-Oligocene uplift, followed by Early Oligocene drowning. This invokes comparisons with parallel observations of the Sarawak margin evolution on north-western Borneo (Kessler and Jong 2016).

Further evidence of strike-slip tectonism in the Malay Basin is given by Md Yazid et al. (2014), the authors described the basin was developed partly as a result of tectonic collisions and strike-slip shear of the Southeast Asia continental slabs, as the Indian Plate collided into Eurasia, and subsequent extrusion of lithospheric blocks towards Indochina:

"The Sunda Block epicontinental earliest rift margins were manifested by the Palaeogene W-E rift valleys, which formed during NW-SE sinistral shear of the region. Later Eocene NW-SE dextral shear of (2nd order) Indochina Block against East Malaya Block rifted open a 3rd order Malay Basin. Developed within it is a series of 4th order N-S en-echelon ridges and grabens. The grabens and some ridges, sequentially, host W-E trending 5th order folds of later compressional episodes. The Malay Basin Ridge and Graben Model explains the multi-phased structural deformation which started with the, a) Pre-Rift Palaeo/Mesozoic crystalline/ metamorphic Basement, b) Syn-rift phase during Paleogene, c) Fast Subsidence from Late Oligocene to Middle Miocene, d) Compressional inversion of first Sunda fold during Late Miocene, and e) Basin Sag during Plio-Pleistocene with mild compressional episodes. The subsequent Mio-Pliocene folding history of Malay Basin is connected to the collision of Sunda Block against subducting Indian-Australian Plate".

Adding to the above model, strike-slip tectonism is also observed in the Tenggol Arch area, which separates the southern edge of the Malay Basin from the Penyu Basin, and also in the small Naga Hitam pull-apart graben offshore Pahang. Further west, however, we see areas of the Peninsula Malaysia rising at least since the Oligocene, and shedding sediment into both the Malay and Penyu basins. The boundary between Oligocene pull-apart basins (Malay, Penyu, Naga Hitam) and Oligocene uplift (Peninsula Malaysia), however, appears difficult to pinpoint.

CONCLUSIONS

Economic viability of deep oil and gas reservoirs depends on the presence of porosity and permeability. The latter is of particular importance, as it controls the production rates of oil and gas. This case study demonstrates that reservoir porosity and permeability prognosis cannot rely on sedimentary facies patterns and compaction criteria alone, and that an understanding of diagenesis is vital. The results of this study could be used to assist in the assessment of the optimum depth for exploration targets in the study area, which suggest that at depths of greater than 3000m tvdss sandstones are likely to have poor reservoir properties. Note also that some vitrinite reflectance data appear to be inconclusive and should be reviewed.

However, it is worth mentioning that the current observations from the rather limited extent of the Penyu Basin may not necessarily hold for the bigger and well-developed Malay Basin, where a number of mechanisms for porosity preservation in deeper reservoirs have been documented. These include grain/rim coating in detrital quartz-rich environment, emplacement of pore spaces by early hydrocarbon migration, secondary porosity development as described in this paper and, preservation of pore spaces by overpressures. The latter overpressure mechanism is believed to be the main common process for porosity preservation of deeper reservoirs in the Malay Basin, and likely the same scenario for the deeper section of J-1 and A-1 wells. Interestingly, and as noted in this study, research by Mohammad Jamaal et al. (2003), suggested the possible role of chemical compaction, which would be facilitated by the high geothermal (gradient> 5°C/100m) in the Malay Basin. Chemical compaction appears to commence around 100 - 110 °C and is independent of overpressure with the associated reduction in permeability that may need to be taken into account for assessing hydrocarbon prospectivity of deeper parts of the basin.

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